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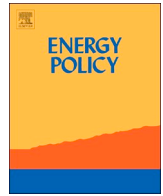
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Transitioning towards negative CO₂ emissions

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ABSTRACT

In this policy perspective we argue that mankind likely needs to achieve negative CO₂ emissions before 2050, describe the transition to CO₂-neutrality and CO₂-negativity, and illustrate the possibly critical role played herein by CO₂ use.

1. Introduction

In order to reach the 1.5 °C maximum temperature increase target of the Paris Agreement, either or not with a temporary overshoot of 2 °C during the 21st century, mankind has to achieve net zero CO₂ emissions in 2050 (IPCC, 2018). This conclusion by the IPCC Special Report on “Global Warming of 1.5 °C”, published in October 2018, has received ample attention in policy making circles and the media. Much less public consideration has been given to the fact that after 2050 substantial net negative CO₂ emissions need to be realized in order to comply with the ambition of not letting the average atmospheric temperature increase exceed 1.5 °C. A net negative balance of CO₂ emissions implies that more CO₂ has to be taken out of the atmosphere than human activities emit into it. We can think of at least six reasons why negative CO₂ emissions should perhaps already materialize before 2050.

First, least developed countries may not be able to achieve a net zero CO₂ economy by 2050, since the availability of cheap fossil fuels is today often still the fastest way to fulfill aspirations of stimulating growth and eradicating poverty. The possibly positive CO₂ emissions in 2050 of some developing countries need to be compensated by negative CO₂ emissions in developed countries, as industrialized nations are responsible for the lion's share of cumulative CO₂ emissions. Second, certain developed countries may fail to reach their net zero CO₂ emission reduction targets, e.g. as a result of a lack of internal political will to transform their economies away from fossil fuels, or because the inertia of the carbon lock-in proves too strong. Their net CO₂ emissions in 2050 must be counterbalanced by negative emissions from other developed countries. Third, in agriculture, forestry and land use

(AFOLU) it may be more difficult to reduce CO₂ emissions than in the use of fossil fuels and industry (FF&I). Net positive CO₂ emissions in 2050 in AFOLU need to be compensated by negative emissions in FF&I. Fourth, within FF&I, for some sectors like aviation and shipping it may be hard to achieve CO₂-neutrality over the next 30 years. Their possibly remaining emissions by 2050 should be offset by negative CO₂ emissions in, for instance, the electricity sector where the switch to zero-CO₂ options is easier and less costly. Fifth, the assumption of net-zero CO₂ emissions strongly depends on substantial emission reductions for two other important greenhouse gases, CH₄ and N₂O (IPCC, 2018), which are usually harder to control and more expensive to mitigate. A potential failure to achieve significant CH₄ and N₂O emission reductions over the next few decades must be counterweighed by negative CO₂ emissions before 2050. Sixth, net CO₂-neutrality in 2050 yields an approximately 70% probability of reaching the 1.5 °C goal of the Paris Agreement. If one wants to raise this probability to e.g. 90%, net CO₂ emissions need to be negative in less than 30 years.

The work by the IPCC heavily hinges on scenarios developed by integrated assessment models (IAMs; IPCC, 2018). The two main options available in most IAMs for implementing net zero or negative CO₂ emissions are (1) AFOLU, and (2) BECCS (biomass energy in combination with CO₂ capture and storage, or CCS). Thus far, IAMs have rarely accurately simulated a third category of methods for realizing net zero or negative CO₂ emissions, that is, processes that use CO₂ as main building block for the production of chemicals, hydrocarbons, materials, and plastics (often referred to as CO₂ capture and usage, or CCU). These alternatives can deliver a “circular carbon economy” (see, for instance, Stahel, 2016). In such an economy all carbon-based products are manufactured from renewable carbon feedstock, either via direct

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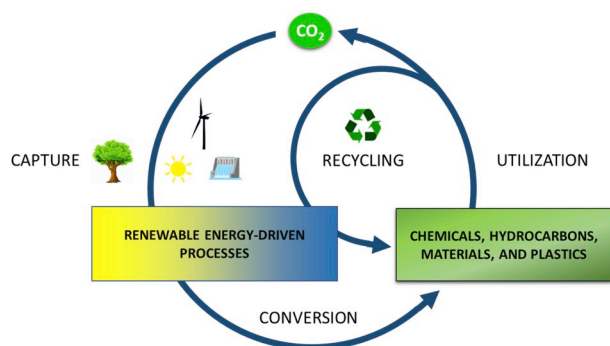


Fig. 1. An idealized circular carbon economy.

atmospheric CO₂ capture (also called direct air capture, or DAC; see Keith, 2009; Lackner et al., 2012), or indirectly via the conversion of waste or biomass derived from natural photosynthesis. We assume that the energy required to drive the capture, conversion, utilization, and recycling processes in an idealized circular carbon economy is provided by CO₂-free renewable resources (see Fig. 1).

The use of CO₂ – or more generally the application of carbon circularity – for the production of chemicals, hydrocarbons, materials, and plastics is at present an activity of around 545 MtCO₂/yr (mostly for the manufacturing of urea and biofuels, and the recycling of packaging; see Table 1; Aresta et al., 2013; Armstrong and Styring, 2015; Mikkelsen et al., 2010). This amount is negligible in comparison to today's level of around 38 GtCO₂/yr anthropogenic CO₂ emissions. Based on potential average growth extrapolations drawn from the literature, we calculate that the level of CO₂ used in a circular carbon economy could become about 14 GtCO₂/yr in 2050 (see Table 1, as well as the online appendix, in which we specify in detail all underlying assumptions). We determine this number by estimating the possible future demand of CO₂ for the production, in particular, of: (A) chemicals, such as alcohols (for instance methanol) and fertilizers (notably urea); (B) hydrocarbons like bitumen and tar e.g. for roads (and applications like roofing), but also fuels and lubricants e.g. for transport (such as in trucks, ships, and planes) (C) materials for construction (e.g. CaCO₃ and MgCO₃ for concrete); and inorganic salts (e.g. Na₂CO₃); and (D) a large variety of plastics and fibers for packaging, textiles, and construction (including e.g. machinery) part of which ends up in landfill. The (short cyclic) fabrication plus use processes behind most carbon-based products listed in Table 1 can lead to net zero CO₂ emissions (here called 'type I'). A share of the utilized CO₂ is stored in products for at least decades – usually centuries or more – and thus offers a potential for (long cyclic) negative CO₂ emissions (called 'type II'). We argue that the numbers listed in Table 1 ought to be accounted for in IAMs if these models are to adequately inform policy makers regarding the feasibility of reaching the Paris Agreement (cf. Gasser et al., 2015; Andersen and Peters, 2016; Kätelhön et al., 2019).

In Fig. 2 we show how the demand for CO₂ in a gradually more circular carbon economy could grow from 545 MtCO₂/yr today to 14

GtCO₂/yr in 2050 (depicted on the positive y-axis as the sum of our four categories, including both type I and II use). Four main options can supply the CO₂ required to meet this demand (shown on the negative y-axis): biomass, DAC, large CO₂ point sources (fossil fuel based or in industry), and recycling and waste streams (see the online appendix for our underlying assumptions). For each of these alternatives we assume feasible growth rates, such that supply matches demand. The first two options capture CO₂ from the atmosphere and yield net zero or negative CO₂ emissions. The third option adds CO₂ from fossil resources or minerals to the economy and at best involves net zero CO₂ emissions – although attractive for early CO₂ use projects, this route should ultimately be limited to nearly unavoidable emissions (e.g. from cement plants). The fourth option prevents additional release of CO₂ into the atmosphere by reusing, recycling, and reconverting carbon-based products before incineration, and thereby lowers the overall demand for CO₂.

The circular carbon economy that we project for 2050 can yield negative CO₂ emissions, as demonstrated in Fig. 3 illustrating the CO₂ streams captured, converted, and utilized in processes driven by renewable energy. Chemicals, hydrocarbons, materials, and plastics – that can be produced via many kinds of conversion methods (Ampelli et al., 2015; Bazzanella and Ausfelder, 2017; Detz et al., 2018; GCCSI, 2011) – can jointly store CO₂ at a level of about 14 GtCO₂/yr, either temporarily or on a longer time scale. Emissions of CO₂ can result from combustion, decomposition, and incineration of these products over starkly diverging timeframes. Some products can be recycled after a relatively short lifetime, while others store CO₂ for centuries or more. If the quantity of CO₂ stored annually in products exceeds the amount of CO₂ produced from remaining fossil fuel usage and industry, the atmospheric CO₂ concentration decreases, in our case by 2 GtCO₂/yr. Changes in AFOLU, as well as the realization of BECCS, could further lower the ambient CO₂ concentration.

Different IAMs adopt broadly varying realizations of AFOLU and BECCS to achieve net negative CO₂ emissions, as exemplified by the four pathways (P1 to P4) described in IPCC (2018). In Fig. 4 we show how global net CO₂ emissions could become negative before 2050 if one gradually transitions towards the circular carbon economy described above. We assume that CO₂ emissions from fossil fuels and industry reduce significantly (but not down to zero) thanks to zero-carbon options like renewables and CCS, energy efficiency, and CO₂ use (the latter e.g. via renewable transport fuels; see pathways P2, P3 and P4 in IPCC, 2018). We also assume that as a result of sustainability practices, CO₂ emissions from AFOLU decline to zero by 2050 (see pathway P4 in IPCC, 2018), while BECCS by then yields negative emissions of 2 GtCO₂/yr (in line with pathway P2 in IPCC, 2018). We suppose that also CO₂ use delivers a net effect of negative emissions in 2050 at a level of 2 GtCO₂/yr, in accordance with Fig. 3. In this overall projection, net negative CO₂ emissions of around 2 GtCO₂/yr are reached before 2050. Although the use of CO₂ today is small in comparison to total anthropogenic CO₂ emissions (Abanades et al., 2017; MacDowell et al., 2017), in our scenario a circular carbon economy would make a meaningful contribution to achieving CO₂-neutrality before 2050.

Table 1
Potential for carbon-based products with CO₂ (equivalents) as feedstock.

| Main categories | Subcategories | CO ₂ demand (MtCO ₂ /yr) | | | References |
|-----------------|---------------------------|--|-------------|--------------|--|
| | | 2015 | 2050 type I | 2050 type II | |
| Chemicals | Alcohols and fertilizers | 145 | 1200 | | (Alvarado, 2016; IFA, 2017; OCI, 2016) |
| | Hydrocarbons | Bitumen and tar | < 1 | 1100 | |
| Materials | Fuels and lubricants | 240 | 6500 | | (IRENA, 2018; Lindemann, 2018; Shell, 2018) |
| | Plastics | Concrete and salts | 30 | 2000 | |
| Plastics | Packaging and textiles | 41 | 1900 | | (Sandalow et al., 2017; Scrivener et al., 2016; Zevenhoven et al., 2006) |
| | Construction and landfill | 89 | 900 | | |
| | Total | 545 | 9600 | 4000 | 13600 MtCO₂/yr in 2050 |

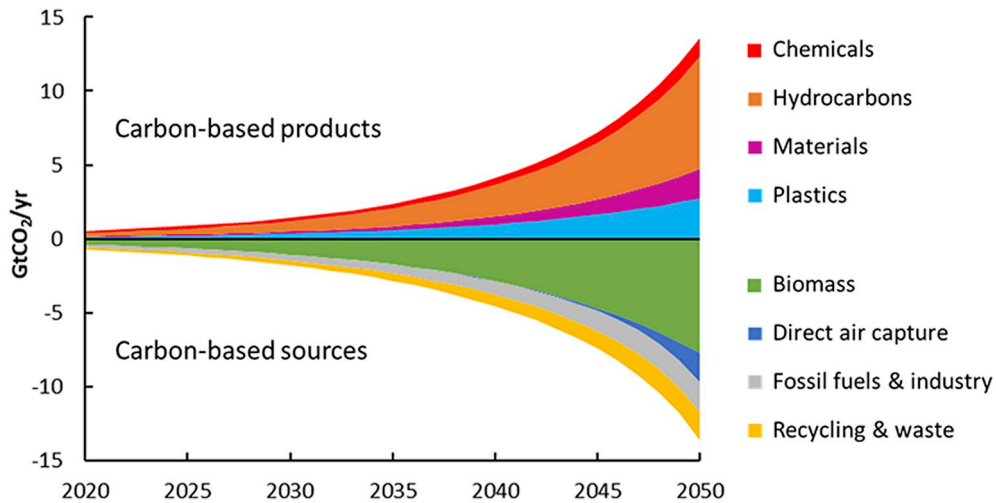


Fig. 2. Projected growth of CO₂ demand and supply.

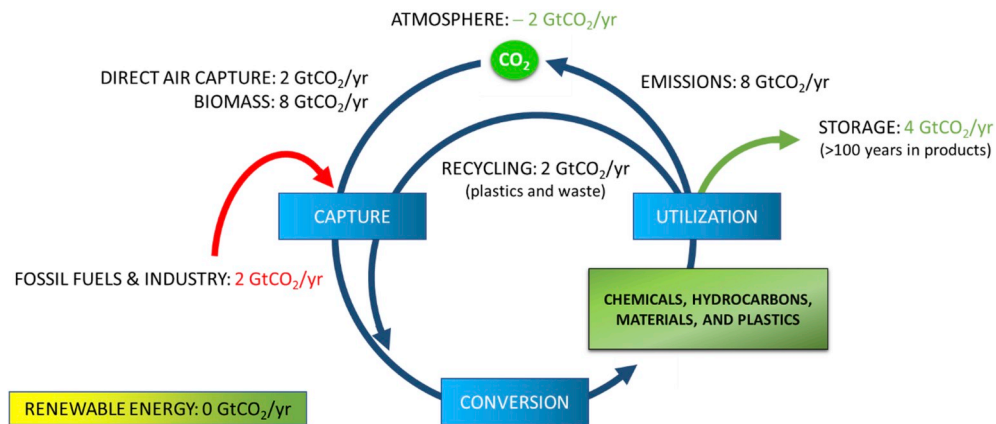


Fig. 3. Main elements of a circular carbon economy in 2050 with net negative CO₂ emissions.

In conclusion, we argue that mankind should prepare for achieving net negative CO₂ emissions before 2050. Observations that during recent years global greenhouse gas emissions have been increasing reinforces this view. We here have shown that CO₂ use can contribute meaningfully to achieving net negative CO₂ emissions before 2050. The technical means to do so, while available on the drawing board and in laboratories, cannot yet readily be scaled up to the required volumes.

We therefore recommend to step up RD&D efforts into a broad set of CO₂ use processes, to determine which approaches work best and can operate with the lowest possible cost, energy penalty, and environmental impact (Artz et al., 2018; Detz et al., 2018; van der Giesen and Kramer, 2014). The broader societal requirements and implications of CO₂ use also need to be studied in depth and from a multidisciplinary perspective. Such research may confirm that more opportunity for

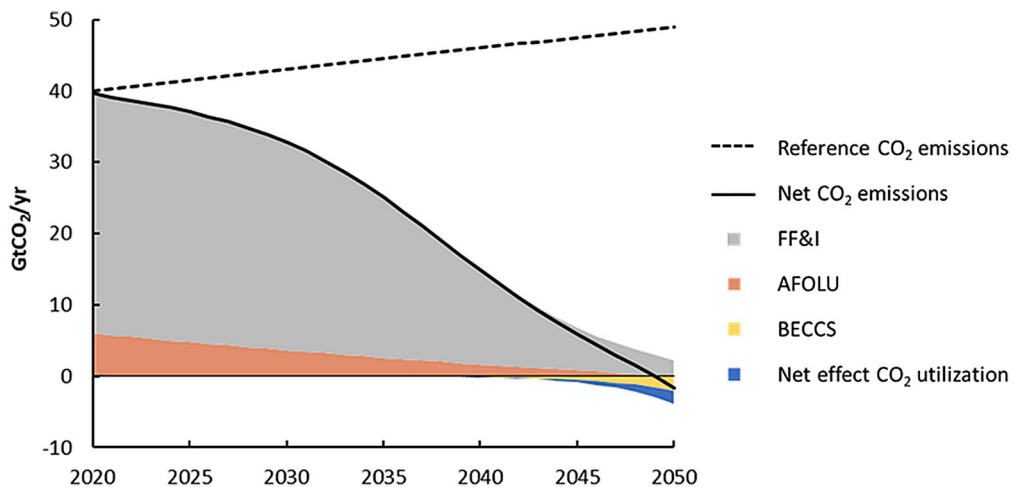


Fig. 4. Transitioning to global net negative CO₂ emissions with a contribution from CO₂ use.

reaching negative CO₂ emissions is available than currently assumed in IAMs if one accounts for all possible CO₂ use processes.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enpol.2019.110938>.

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